Development of a dynamic visco-elastic vehicle-soil interaction model for rut depth, energy and power determinations

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Presentation Outline

A) Review of Soil Model governing equations

B) Development of pedo-transfer functions (terrain database to engineering properties)

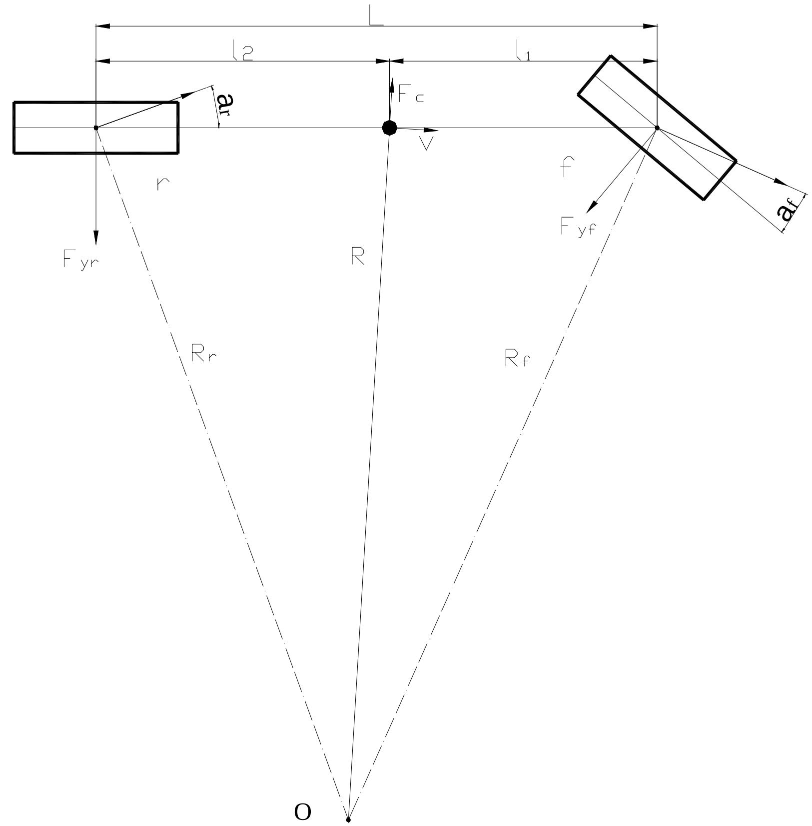
C) Ethan Allen Firing Range (EAFR) terrain database conversion

D) Dynamic Soil Model example (Stryker tire with EAFR soil)

A) Soil Model Governing Equations

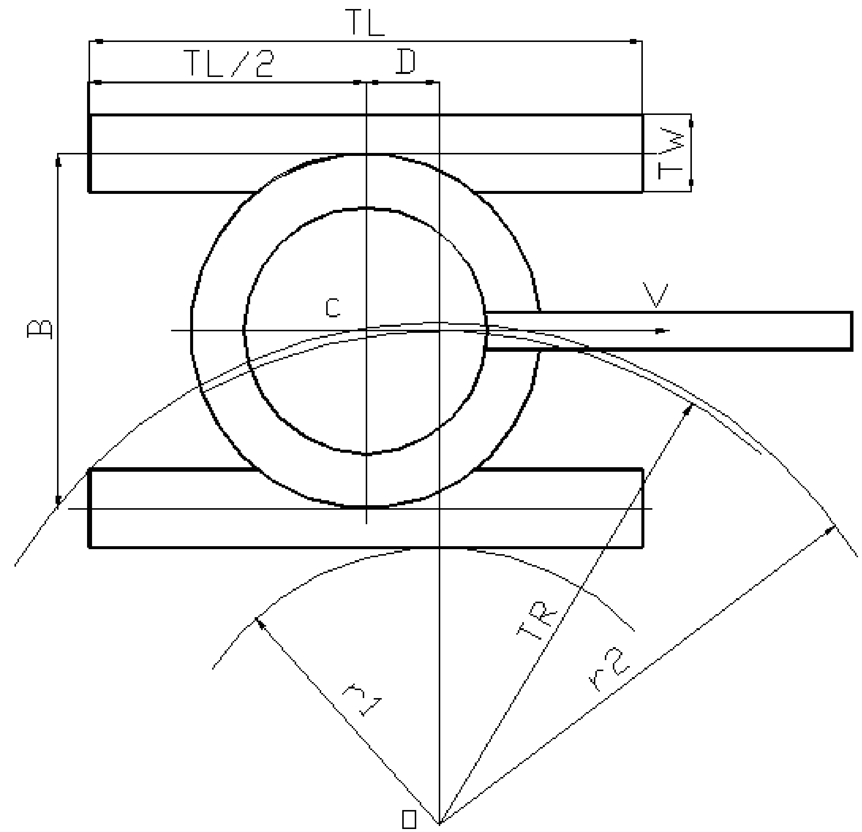
1) Boussinesq/Cerruti vertical stress distribution
2) Soil response - Vertical visco-elasto-plastic displacement
3) Shear stress/deformation
   - Slip (longitudinal), Turning (lateral)
   - Bulldozing

Disturbed width for Wheeled vehicles (4 wheel)



$$DW = \frac{L}{\sin(\frac{L}{TR - B/2})} \cdot \left(\sin(\frac{\pi}{2} - \frac{W_r}{C_{\alpha r}} \frac{V^2}{g \cdot TR}) - \sin(\frac{\pi}{2} + \frac{W_r}{C_{\alpha r}} \frac{V^2}{g \cdot TR} - \frac{L}{TR - B/2}) \right) + TW$$

Disturbed width for tracked vehicles



$$DW = \sqrt{\left(\frac{TL}{2} + \frac{v^2 \cdot TL}{4g\mu_l \cdot TR}\right)^2 + \left(TR - \frac{B}{2} + \frac{TW}{2}\right)^2} - \left(TR - \frac{B}{2} - \frac{TW}{2}\right)$$

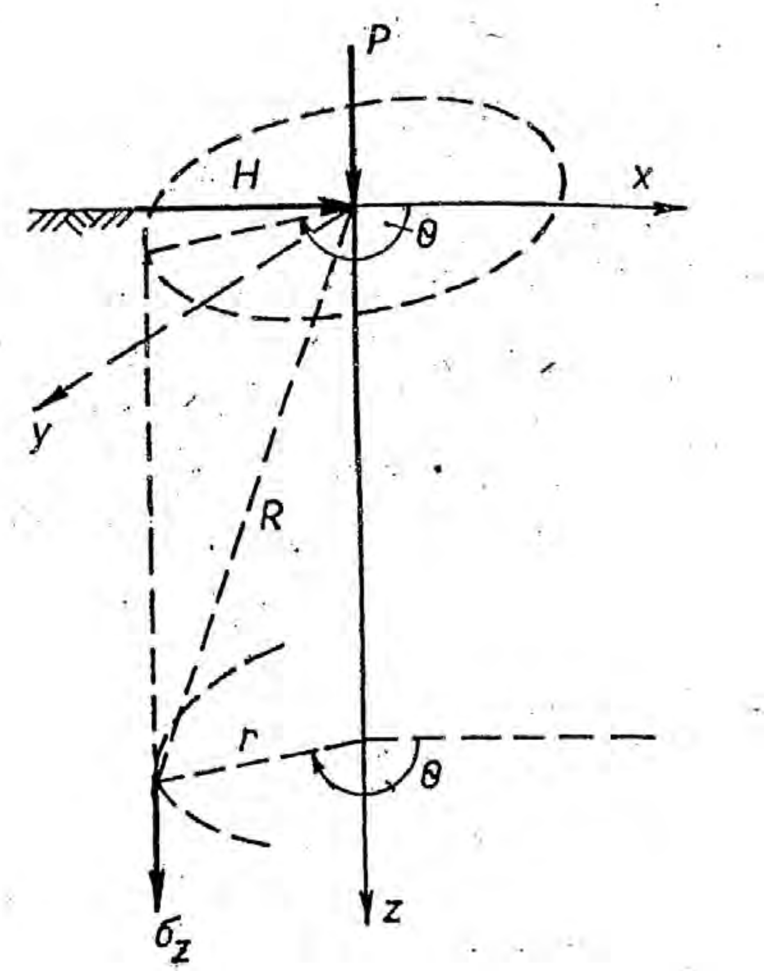
Compression Model Approaches

"Essentially, all models are wrong, but some are useful." --- George Box

- Wheel numerics – Dimensionless numbers
- Bekker equation
- Boussinesq stress and Compression Index
- FEM or DEM

Boussinesq Vertical Stress Distribution due to Vertical Force

$$\sigma_z = \frac{3Pz^3}{2\pi[(x^2 + y^2 + z^2)]^{5/2}}$$

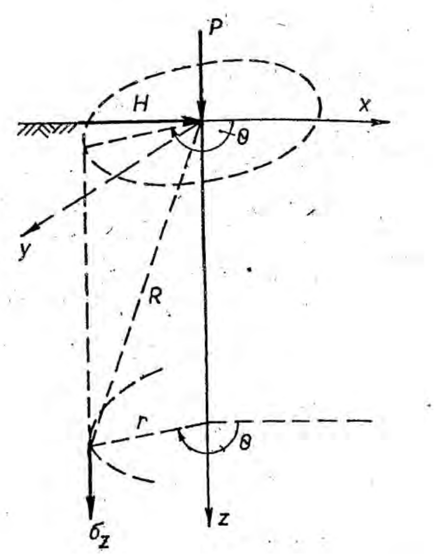


from Feda, 1978

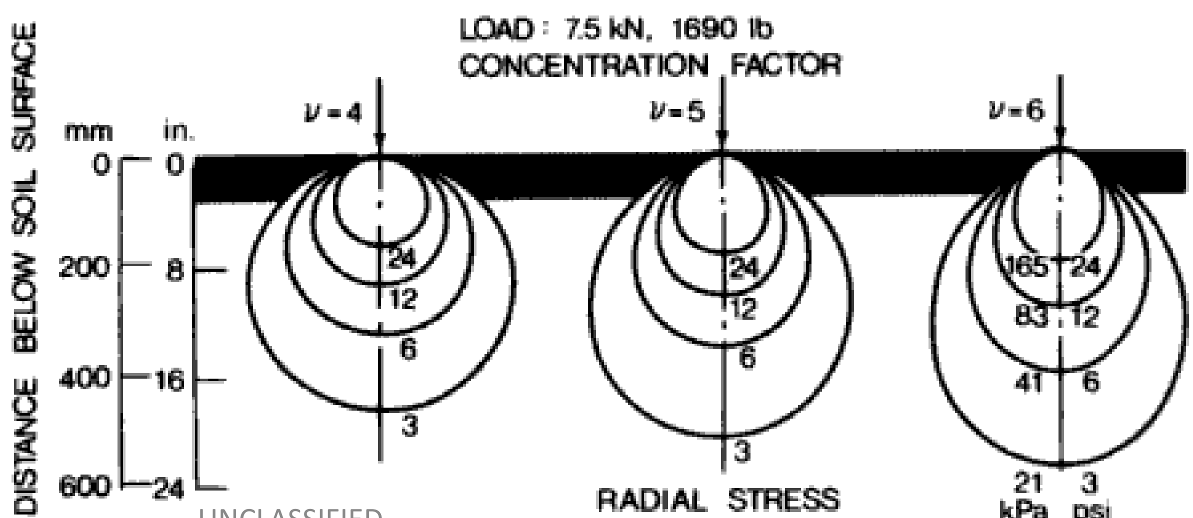
Boussinesq Stress Distribution

- Assumes soil follows the theory of elasticity
- Assumes contact area of the tire is a rectangular plate
- Modified equation with Frohlich's concentration factor

$$\sigma_z = \frac{\nu W z^{\nu}}{2\pi(x^2 + y^2 + z^2)^{(\nu/2+1)}}$$



(Source: Feda, 1978)



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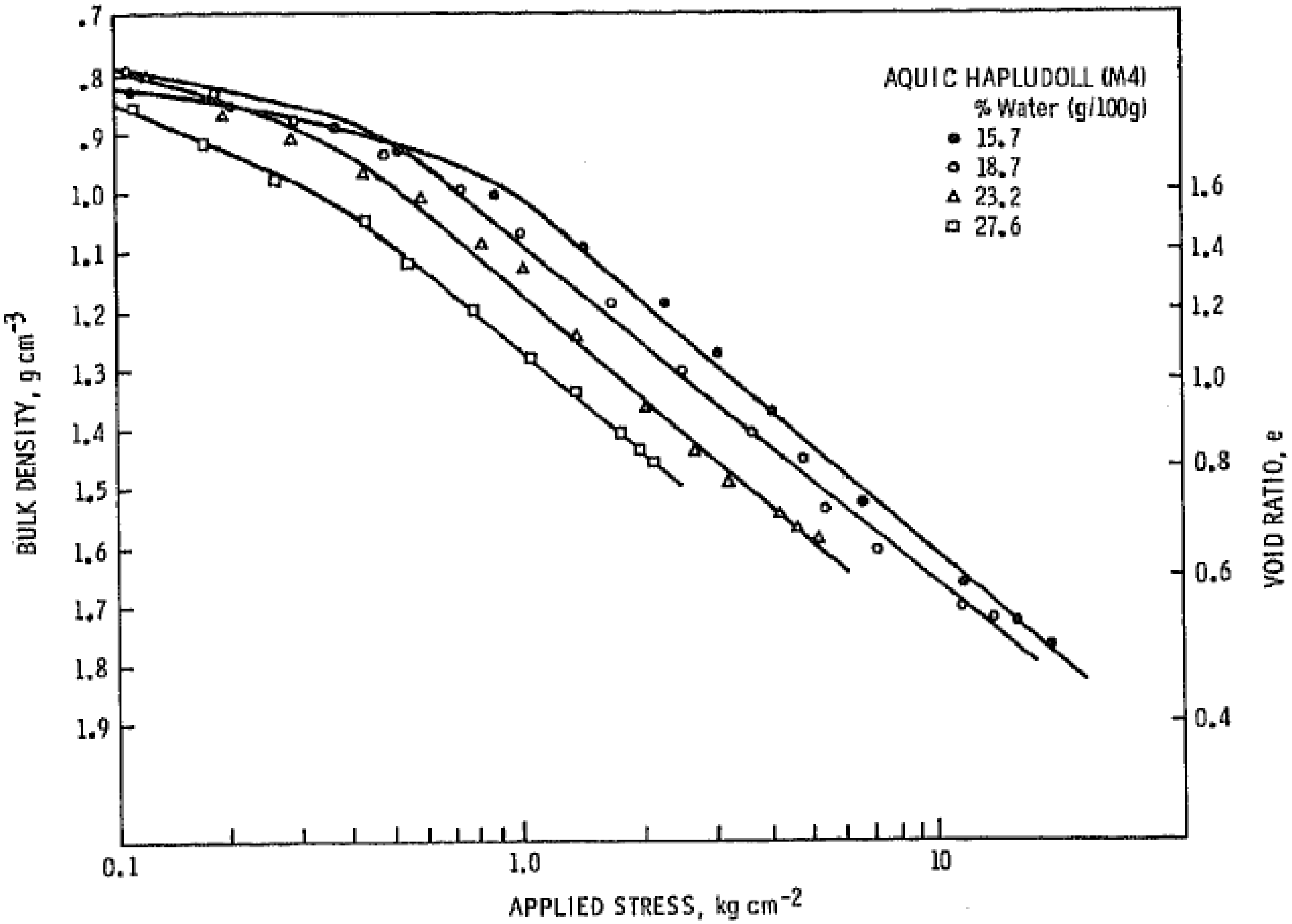
(Source: Wong, 2008)

2) Soil response - Vertical visco-elasto-plastic displacement

- Compression index
- Influence of soil type and moisture
- Rebound
- Time dependent sinkage

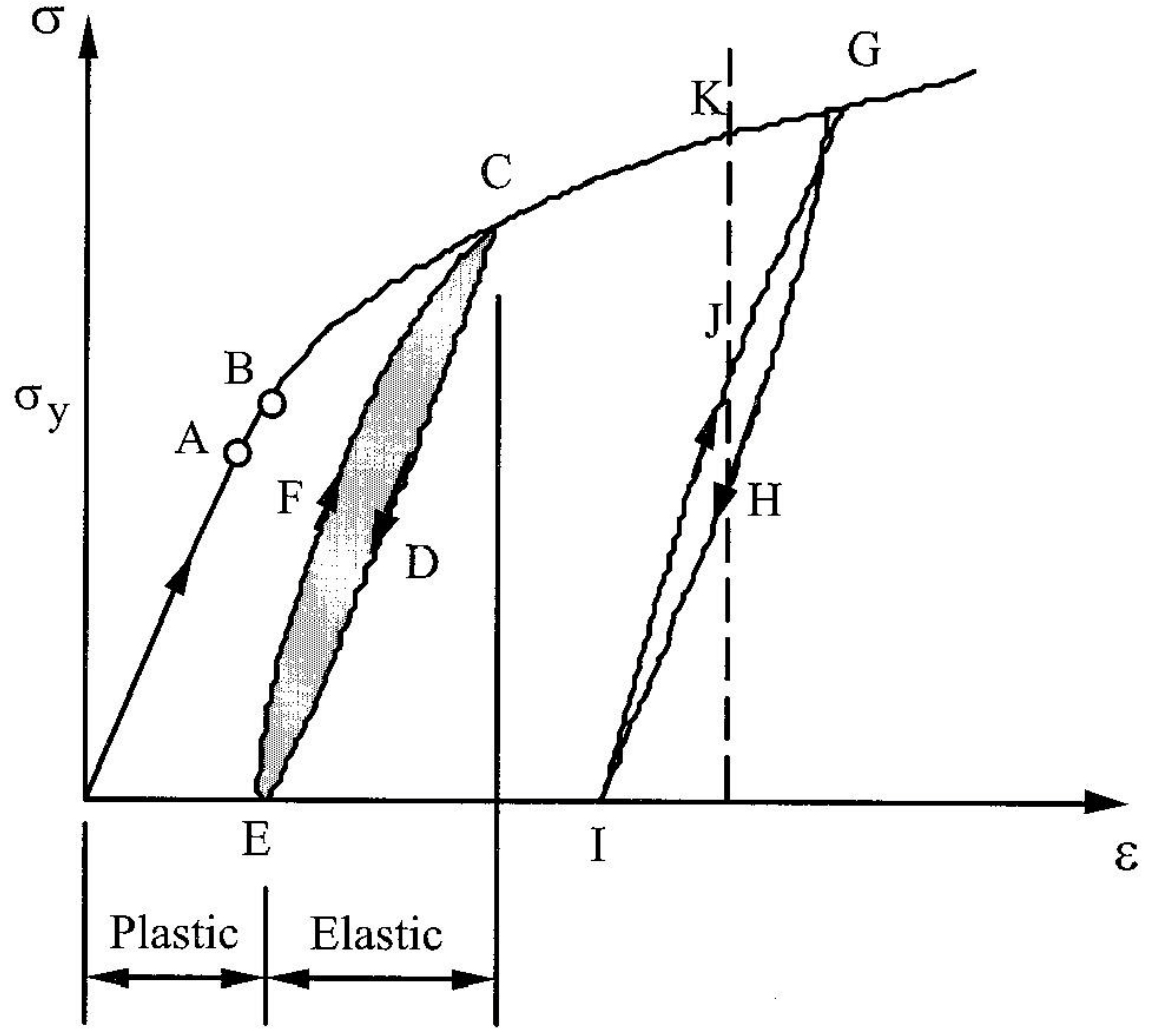
$$\rho = \left[\rho_k + S_T\left(S_1 - S_k\right)\right] + C\log\left(\sigma_a / \sigma_k\right)$$

where S_T, S_1 and S_k are the moisture factors



from Larson et al., 1980

Elasto-plastic deformation (rebound)



from Upadyhaya et al., 2002

3) Shear stress/deformation

- Lateral/longitudinal stress-strain, shear deformation modulus (Janosi/Wong)
- Bulldozing (soil displacement) analysis, passive lateral earth pressure

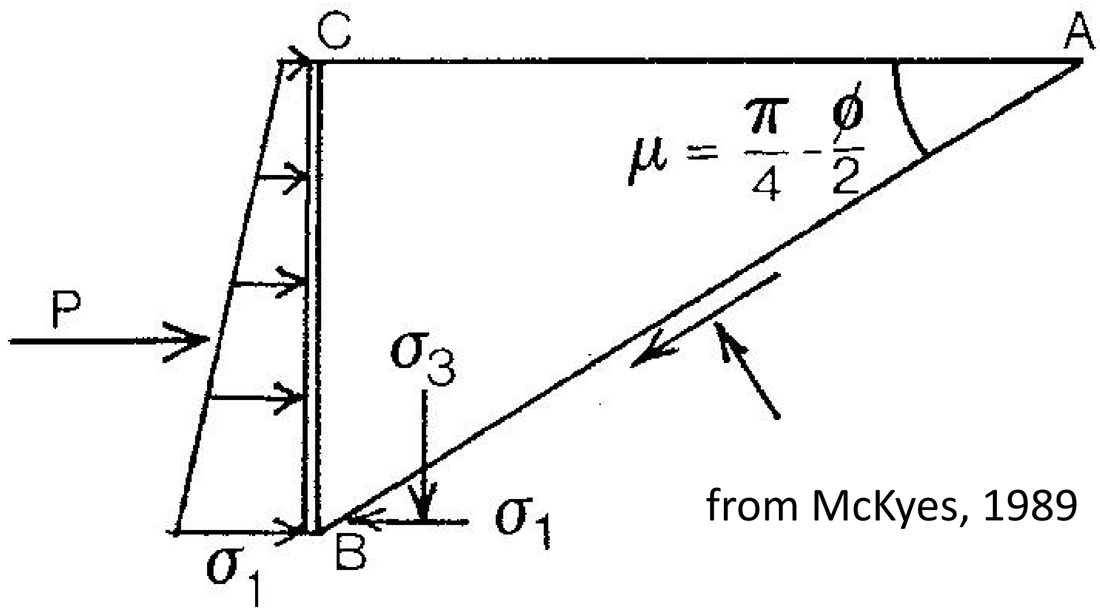
Lateral shear deformation modulus slip displacement

$$\tau = \tau_{\max} \cdot \left(1 - e^{-j/K}\right) = \left(c + \sigma \cdot \tan\phi\right) \cdot \left(1 - e^{-j/K}\right)$$

- Where τ is the shear stress,
- j is the shear displacement,
- c is the internal cohesion of the soil,
- ϕ is the angle of internal friction of the soil,
- K is defined as the shear deformation modulus (Wong, 2001).

"Bulldozer" forces

(passive lateral earth pressure)



from McKyes, 1989

$$P = b(\tfrac{1}{2}\gamma Z^2 N_\phi + 2cZ\sqrt{N_\phi})$$

$$N_\phi = \tan^2(45 + \phi/2)$$

B) Development of pedo-transfer functions

Engineering parameters needed by soil model

- compression index
- rebound index
- time constant
- cohesion
- friction angle
- shear deformation modulus
- density

Ethan Allen Firing Range Database (what we are starting with)

Elevation >= 0

Hex code	Decimal code	Terrain Condition	Soil Type	Moisture content code	RCI 0-6 psi	RCI 6-12	Snow Depth	Snow Density	Frost Depth	Thaw Depth
4A00	18944	NFG	ML	NOR	50	80	0	0	0	0
4A02	18946	NFG	ML	NOR	50	80	0	0	0	0

Elevation > 152

Hex code	Decimal code	Terrain Condition	Soil Type	Moisture content code	RCI 0-6 psi	RCI 6-12	Snow Depth	Snow Density	Frost Depth	Thaw Depth
5300	44308	NFG	CL	SLP	80	80	0	0	0	0
5300	21248	NFG	CL	SLP	80	80	0	0	0	0
5304	21252	NFG	CL	SLP	80	80	0	0	0	0
530C	21260	NFG	CL	SLP	80	80	0	0	0	0
5314	21268	NFG	CL	SLP	80	80	0	0	0	0
532C	21292	NFG	CL	SLP	80	80	0	0	0	0
5334	21300	NFG	CL	SLP	80	80	0	0	0	0
5340	21312	NFG	CL	SLP	80	80	0	0	0	0
5344	21316	NFG	CL	SLP	80	80	0	0	0	0

Terrain database descriptors (off-road soil conditions):

- Terrain Condition - Fine-grained soil NFG, coarse-grained soil NCG, road, other.
- Soil Type - Uses Unified Soil Classification System (USCS) CL, CH, ML)
- Moisture content code – NOR (normal) and SLP (slippery) for fine-grained soil, normal for coarse-grained soil)
- RCI 0-6 - Soil strength 0-6 inches, RCI for fine-grained soils, CI for coarse-grained soils.
- RCI 6-12 - Soil strength 6-12 inches, RCI for fine-grained soils, CI for coarse-grained soils.

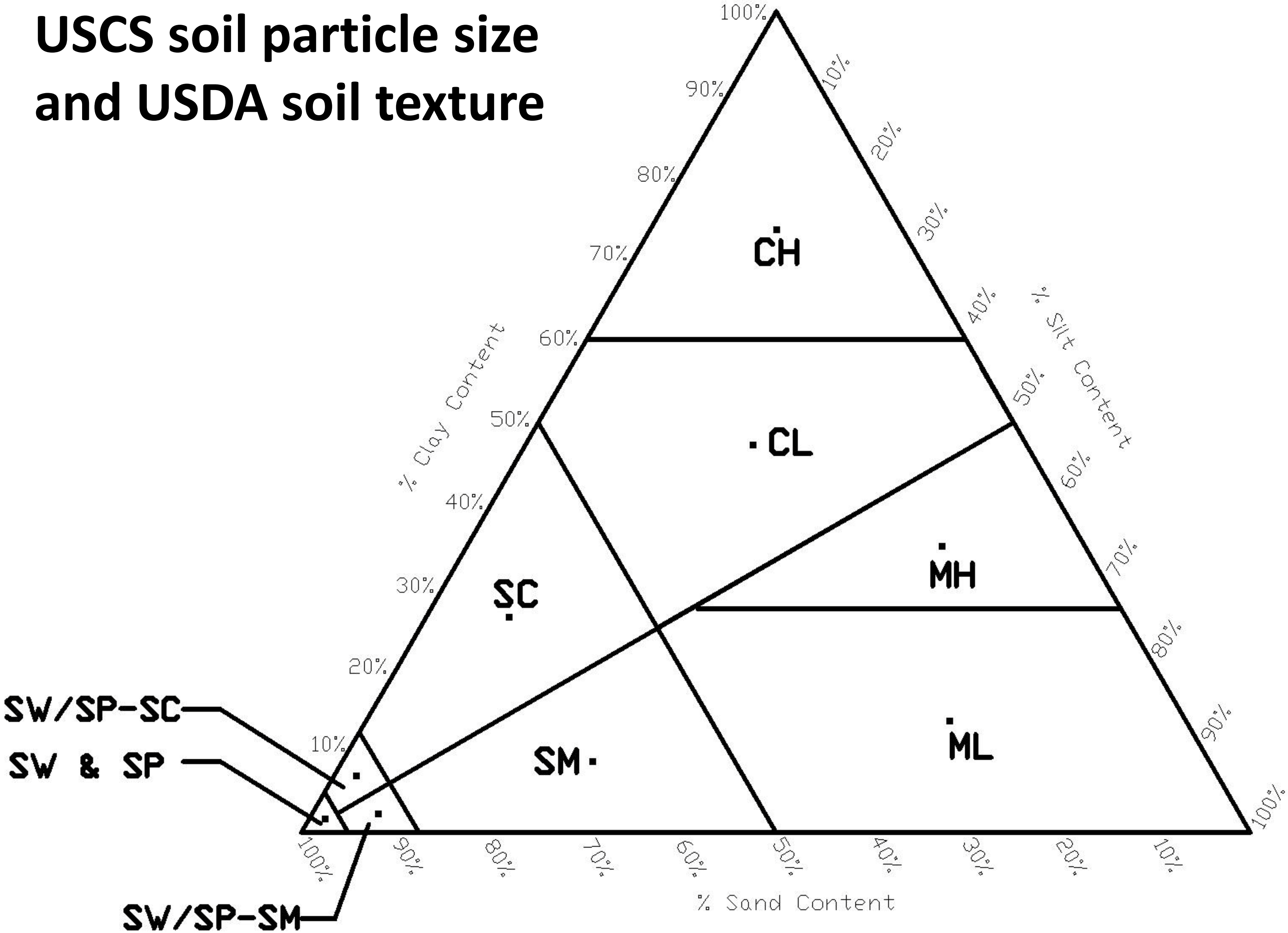
Pedo-transfer function

- Need to transfer existing terrain database descriptors to soil engineering properties.

Unified Soil Classification System (USCS)

MAJOR DIVISIONS			GROUP SYMBOLS	TYPICAL NAMES	FIELD INDENTIFICATION PROCEDURES (excluding particles larger than 3 inches and basing fractions on estimated weights)			INFORMATION REQUIRED FOR DESCRIBING SOILS
1	2		3	4	5			6
Coarse-grained Soils More than half of material is larger than No. 200 sieve size.	Gravels More than half of coarse fraction is larger than No. 4 sieve size.	(Clean Gravels Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	Wide range in grain sizes and substantial amounts of all intermediate particle sizes			For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics. Give typical name: Indicate approximate percentage of sand and gravel, maximum size, angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information, and symbol in parentheses. Example: Silty sand gravelly; about 20% hard, angular gravel particles 1/2in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% non plastic fines with low dry strength; well compacted and moist in place; alluvial sand (SM).
			GP	Poorly graded gravels or gravel-sand mixtures, little or no fines	Predominatly one size or a range of sizes with some intermediate sizes missing			
		(Gravels with Fines Appreciable amount of fines)	GM	Silty gravels, gravel-sand-silt mixtures	Nonplastic fines or fines with low plasticity (for identification procedures see ML below)			
			GC	Clayey gravels, gravel-sand-clay mixtures	Plastic fines (for identification see CL below)			
	Sands More than half of coarse fraction is smaller than No. 4 sieve size (For visual classification, the ¼-in. size may be used as equivalent to the No. 4 sieve)	Clean Sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines	Wide range in grain sizes and substantial amounts of all intermediate sizes missing			
			SP	Poorly graded sands or gravelly sands, little or no fines	Predominantly one size or a range of sizes with some intermediate sizes missing			
		Sands with Fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures	Nonplastic fines or fines with low plasticity (for identification			
			SC	Clayey sands, sand-clay mixtures	Plastic fines (for identification procedures see CL below)			
The No. 200 sieve size is about the smallest particle visible to the naked eye.					Identification Procedures on Fraction smaller than No. 40 Sieve Size			
					Dry Strength (Crushing Characteristics)	*Dilatancy (Reaction to Shaking)*	*Toughness (Consistency near PL)*	
Fine-grained Soils More than half of material is smaller than No. 200 sieve size.	Silts and Clays Liquid limit is less than 50.		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	None to slight	Quick to slow	None	For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions. Give typical name, indicate degree and character or plasticity, amount and maximum size of coarse grains, color in wet conditions, odor (if any), local or geologic name, and other pertinent descriptive information, and symbol in parentheses. Example: Clayey silt, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry and place; loess (ML).
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Medium to high	None to very slow	Medium	
			OL	Organic silts and organic silty clays of low plasticity	Slight to medium	Slow	Slight	
	Soils and Clays Liquid limit is greater than 50.		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Slight to medium	Slow to none	Slight to medium	
			CH	Inorganic clays of high plasticity, fat clays	High to very high	None	High	
			OH	Organic clays and silts of medium to high plasticity	Medium to high	None to very slow	Slight to medium	
Highly Organic Soils			Pt	Peat and other highly organic soils	Readily identified by color, odor, spongy feel and frequently by fibrous texture			

USCS soil particle size and USDA soil texture



The centroid percent Sand, Silt, and Clay and particle size for 9 USCS Classes

USCS Soil Type	%Clay Avg	%Silt Avg	%Sand Avg	Average Grain Size (mm)	Clay Index (0-5)	Grain Size Index (0-5)
CH	73.3	13.3	13.3	0.35	5.00	5.00
CL	47.2	24.0	28.9	0.76	3.21	2.32
MH	34.8	50.0	15.2	0.41	2.38	4.27
ML	13.6	61.5	24.9	0.67	0.93	2.63
SC	26.2	8.8	65.0	1.69	1.79	1.04
SM	8.8	26.2	65.0	1.70	0.60	1.04
SW/SP-SC	6.9	2.3	90.8	2.36	0.47	0.75
SW/SP-SM	2.3	6.9	90.8	2.36	0.16	0.75
SW & SP	1.7	1.7	96.7	2.51	0.11	0.70

Ethan Allen Firing Range terrain database over 1000 soil units (rows). Ignoring the elevation and non-soil units, a set of 13 unique soil units were identified as shown below.

Terrain	Soil Type	Moisture	RCI
NFG	CL	SLP	80
NFG	GM	NOR	150
NFG	ML	NOR	100
NFG	ML	NOR	65
NFG	ML	NOR	43.5
NFG	ML	NOR	30
OTH	PT	NOR	17.5
NFG	SM	NOR	130
NFG	SM	NOR	110
NFG	SM	NOR	65
NCG	SP	NOR	130
NFG	CL	SLP	130
NFG	SC	SLP	80

Pedo-transfer functions

$$\varphi = 24.03 - 3.06 \cdot (Clay\_Index) + 1.03 \cdot (Grain\_Size\_Index) + .0047 \cdot (RCI)$$

$$c = 8.65 + 12.15 \cdot (Clay\_Index) - 8.94 \cdot (Grain\_Size\_Index) + .0070 \cdot (RCI)$$

$$C = .2175 + .01245 \cdot (\%Clay) - .000131 \cdot (\%Clay)^2$$

$$K = 21.74 - 3.22 \cdot (Clay\_Index) + 0.47 \cdot (GSI)$$

$$\rho = 1.68 - 0.10 \cdot (Clay\_Index) - 0.04 \cdot (GSI)$$

$$\text{Rebound\_Constant} = 0.011 + 0.004 \cdot (GSI)$$

$$\rho_K = 1.544 - 0.00556 \cdot (\%Clay) - 3.468 \times 10^{-5} \cdot (\%Clay)^2$$

$$S_T = 0.003461 + 1.742 \times 10^{-4} \cdot (\%Silt) - 2.980 \times 10^{-6} \cdot (\%Silt)^2 \quad \text{(C, M)}$$

$$S_T = 0.003217 + 3.251 \times 10^{-4} \cdot (\%Clay) - 5.385 \times 10^{-6} \cdot (\%Clay)^2 \quad \text{(S)}$$

C) Predicted Soil Engineering Properties for the EAFR Terrain Codes

Terrain	Soil Type	Moisture	RCI	Clay Index	Grain Size Index	Friction Angle (º)	c (kPa)	K (cm)	C (g/cm3)	Bulk Density,ρ (g/cm3)	Rebound Constant (g/cm3)	Time Constant (s)
NFG	CL	SLP	80	3.21	2.32	17.0	27.4	10	0.51	1.25	0.020	
NFG	GM	NOR	150	--	--	--	--	--	--	--	--	--
NFG	ML	NOR	100	0.93	2.63	24.4	0.0	18	0.36	1.48	0.022	
NFG	ML	NOR	65	0.93	2.63	24.2	0.0	18	0.36	1.48	0.022	
NFG	ML	NOR	43.5	0.93	2.63	24.1	0.0	18	0.36	1.48	0.022	
NFG	ML	NOR	30	0.93	2.63	24.0	0.0	18	0.36	1.48	0.022	
OTH	PT	NOR	17.5	--	--	--	--	--	--	--	--	--
NFG	SM	NOR	130	0.60	1.04	23.9	7.5	19	0.32	1.58	0.015	
NFG	SM	NOR	110	0.60	1.04	23.8	7.4	19	0.32	1.58	0.015	
NFG	SM	NOR	65	0.60	1.04	23.6	7.1	19	0.32	1.58	0.015	
NCG	SP	NOR	130	0.11	0.70	25.0	4.6	21	0.24	1.64	0.014	
NFG	CL	SLP	130	3.21	2.32	17.2	27.8	10	0.51	1.25	0.020	
NFG	SC	SLP	80	1.79	1.04	20.0	21.6	15	0.45	1.45	0.015	

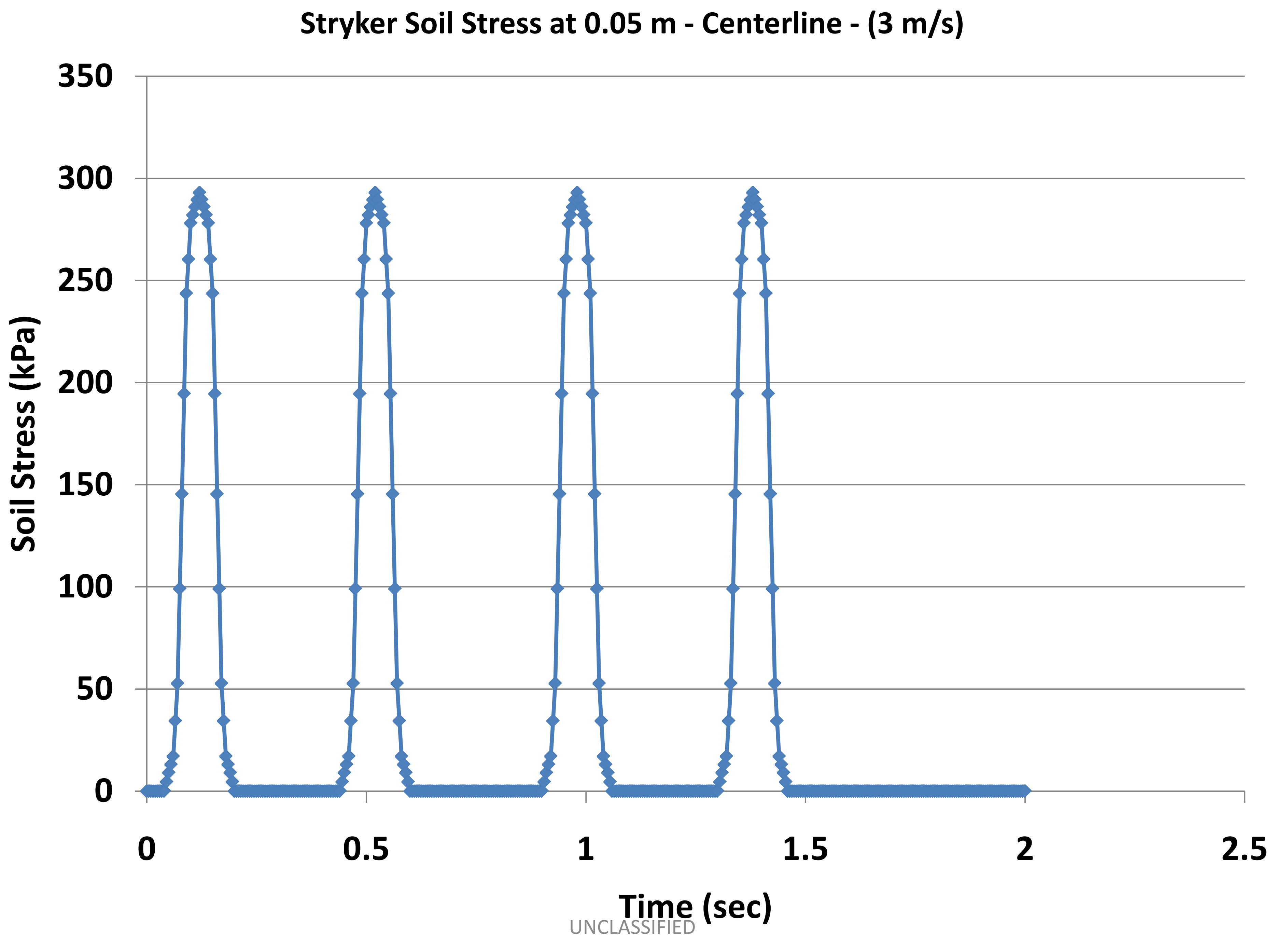
D) Dynamic Soil Compression Model

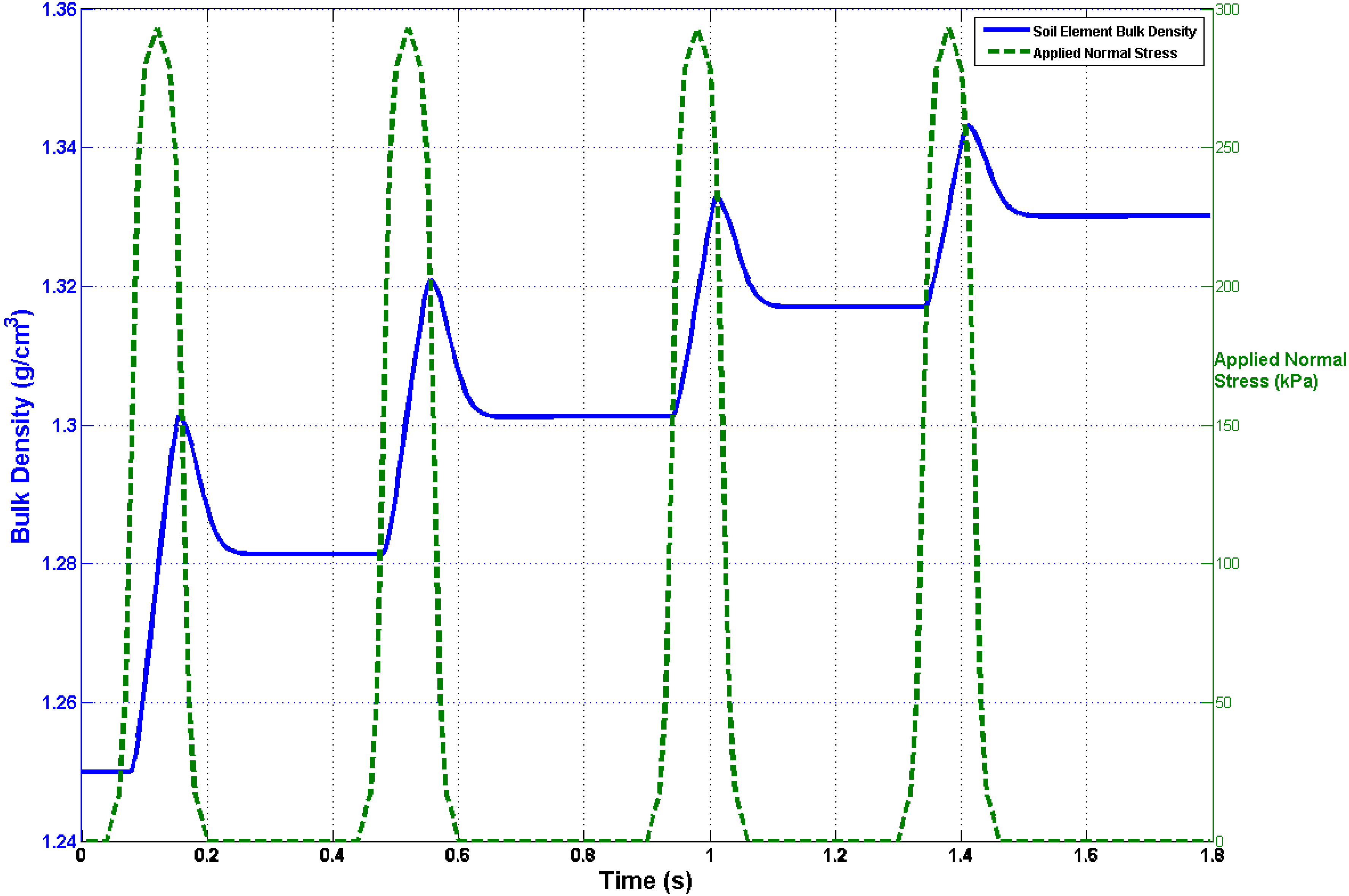
- A 1 cm^3 soil element, 5 cm below the soil surface, positioned along the tire centerline
- EAFR terrain - CL (USCS), 80 psi (RCI), SLP (moisture)
- Simple Stryker tire (22.25 kN normal load) traveling at 3 m/s with a tire inflation pressure of 276 kPa (40 psi). (uniformly distributed rectangular surface load)

EAFR Soil Engineering Properties

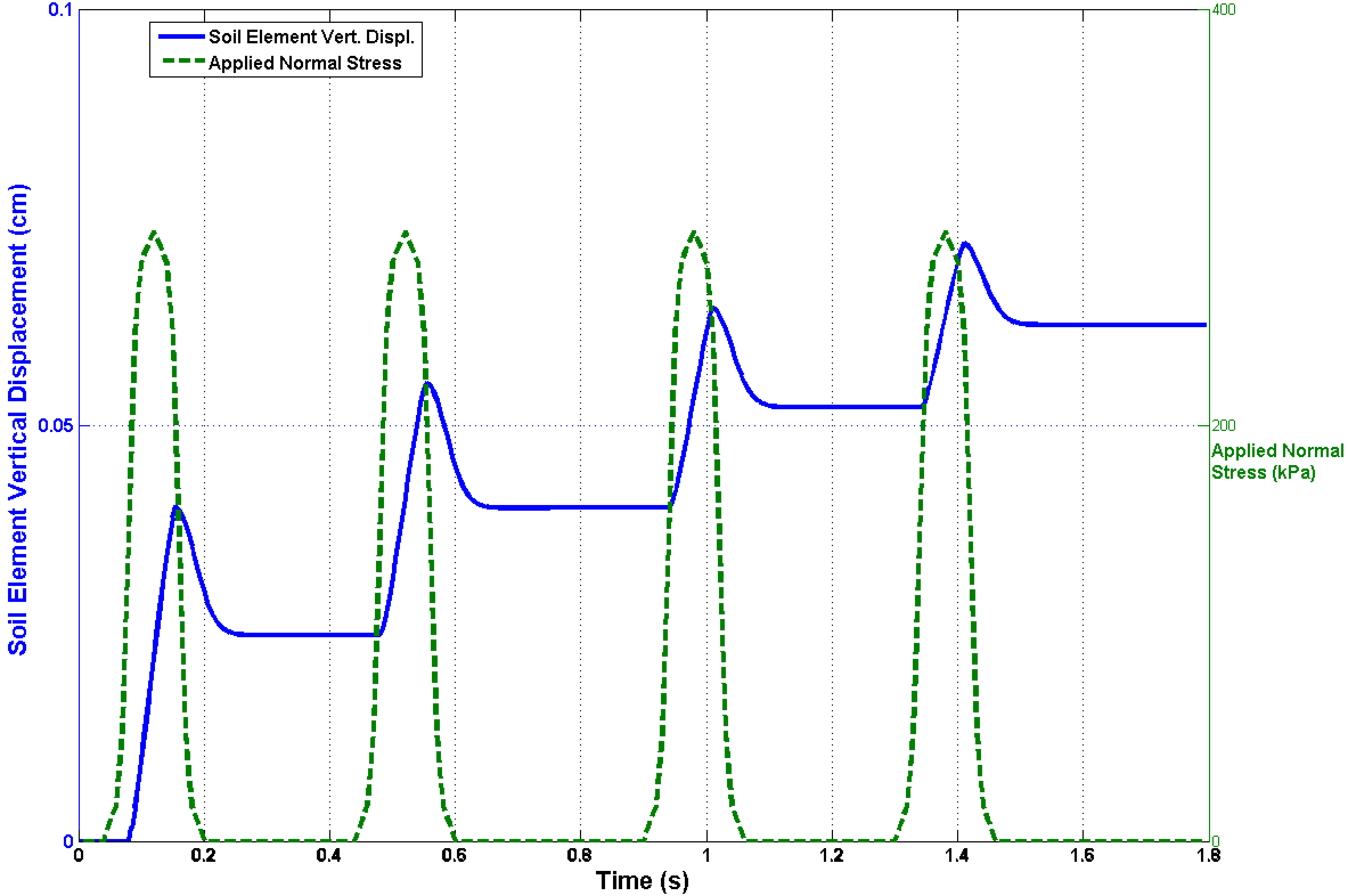
- **Terrain - NFG**
- **Soil Type - CL**
- **Moisture - SLP**
- **RCI - 80**

- **Clay Index - 3.21**
- **Grain Size Index - 2.32**
- **Friction Angle (º) - 17.0**
- **c (kPa) - 27.4**
- **K (cm) - 10**
- **C (g/cm3) - 0.51**
- **Bulk Density, ρ (g/cm3) - 1.25**
- **Rebound Constant (g/cm3) - 0.020**
- **Time Constant (s) – 0.2**

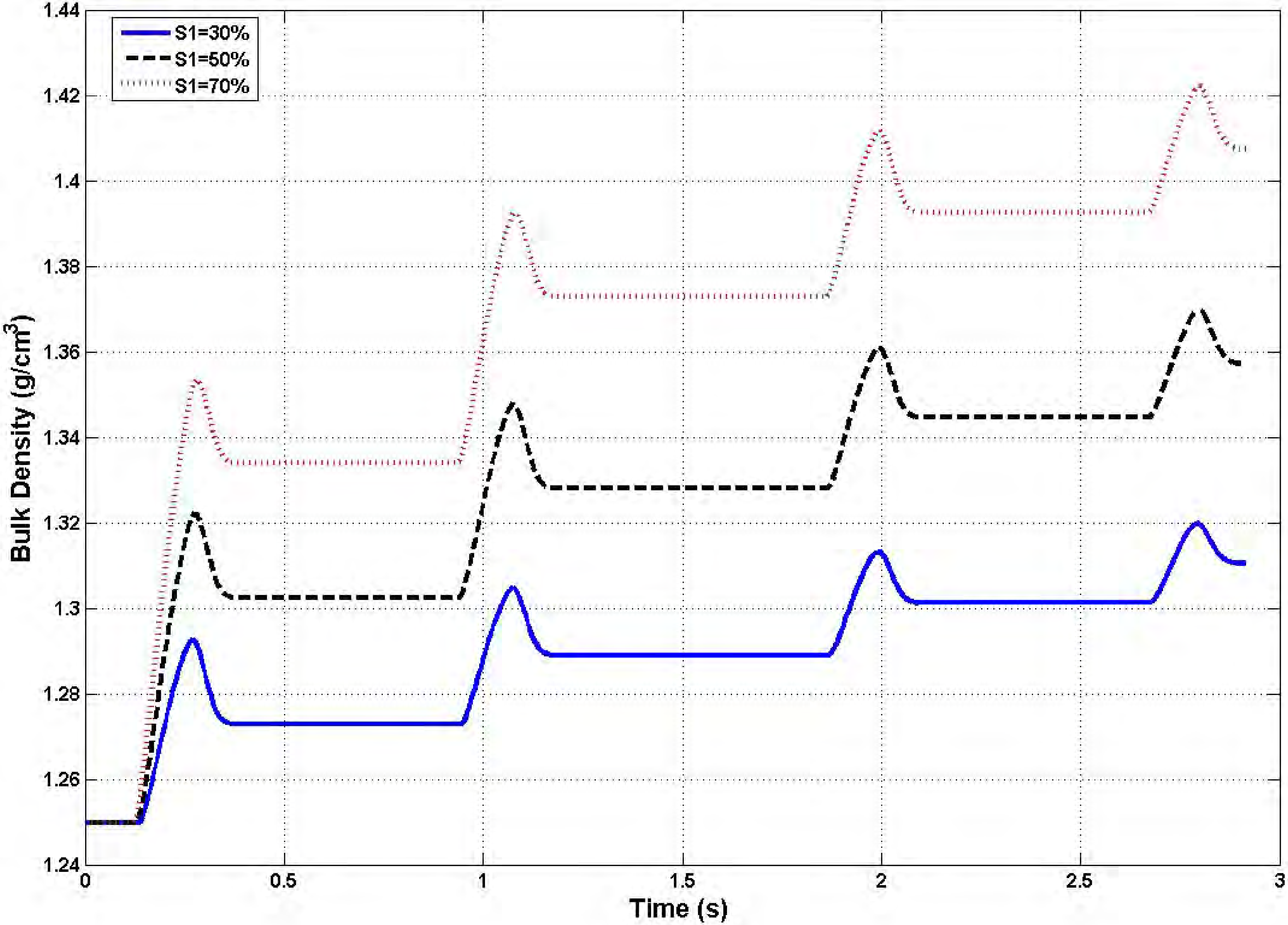

Stryker Soil Stress at 0.05 m - Centerline - (3 m/s)
Soil Stress (kPa)
350
300
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
Time (sec)



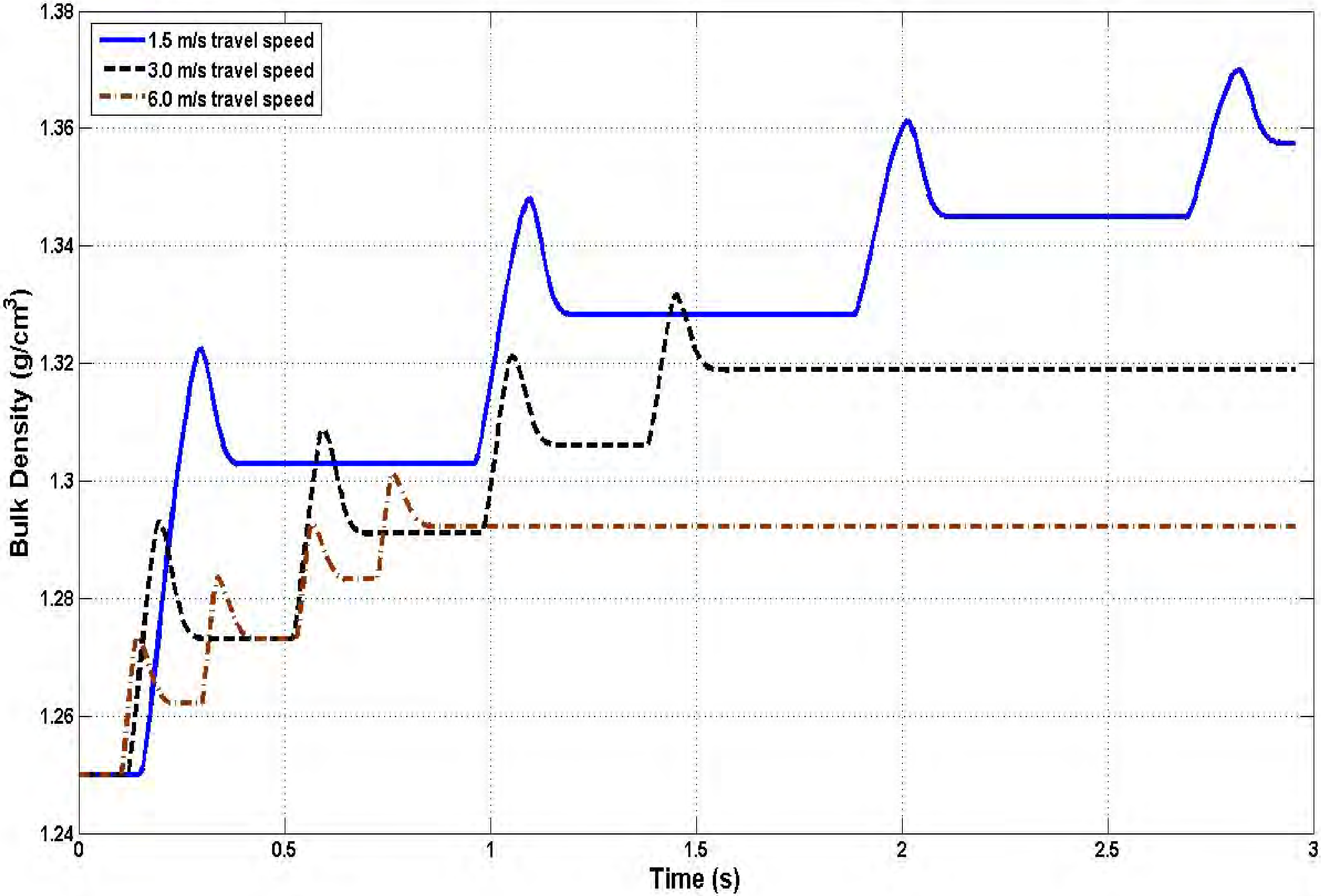
Soil Element Bulk Density
Applied Normal Stress
Bulk Density (g/cm3)
Applied Normal Stress (kPa)
Time (s)
1.36
1.34
1.32
1.3
1.28
1.26
1.24
300
250
200
150
100
50
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8



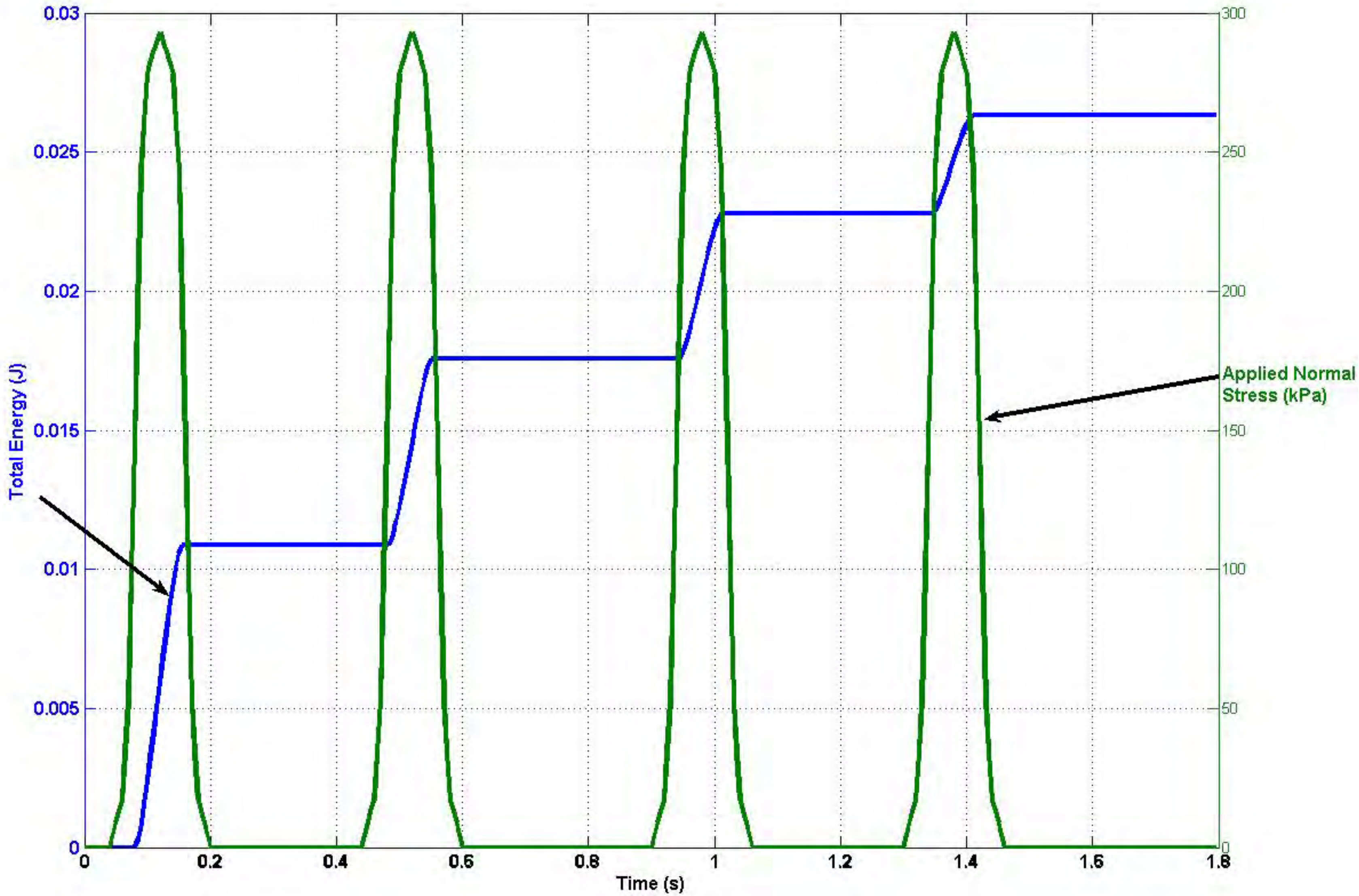
Soil Element Vert. Displ.
Applied Normal Stress
Soil Element Vertical Displacement (cm)
0.1
0.05
0
Applied Normal Stress (kPa)
400
200
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Time (s)



S1=30%
S1=50%
S1=70%
Bulk Density (g/cm³)
Time (s)
1.44
1.42
1.4
1.38
1.36
1.34
1.32
1.3
1.28
1.26
1.24
0
0.5
1
1.5
2
2.5
3


1.5 m/s travel speed
3.0 m/s travel speed
6.0 m/s travel speed
Bulk Density (g/cm3)
Time (s)
1.38
1.36
1.34
1.32
1.3
1.28
1.26
1.24
0
0.5
1
1.5
2
2.5
3

Model E Output



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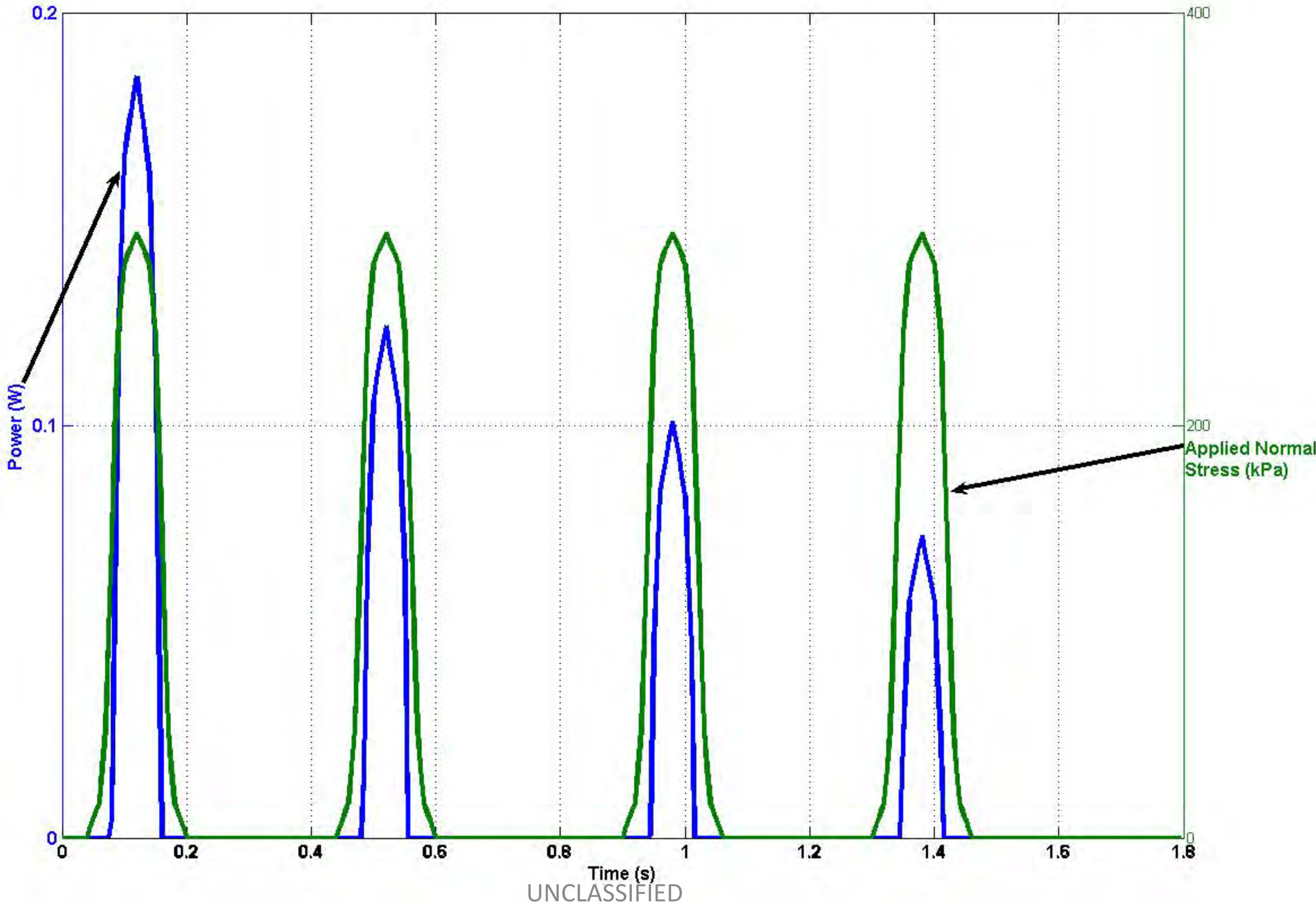
Model P Output



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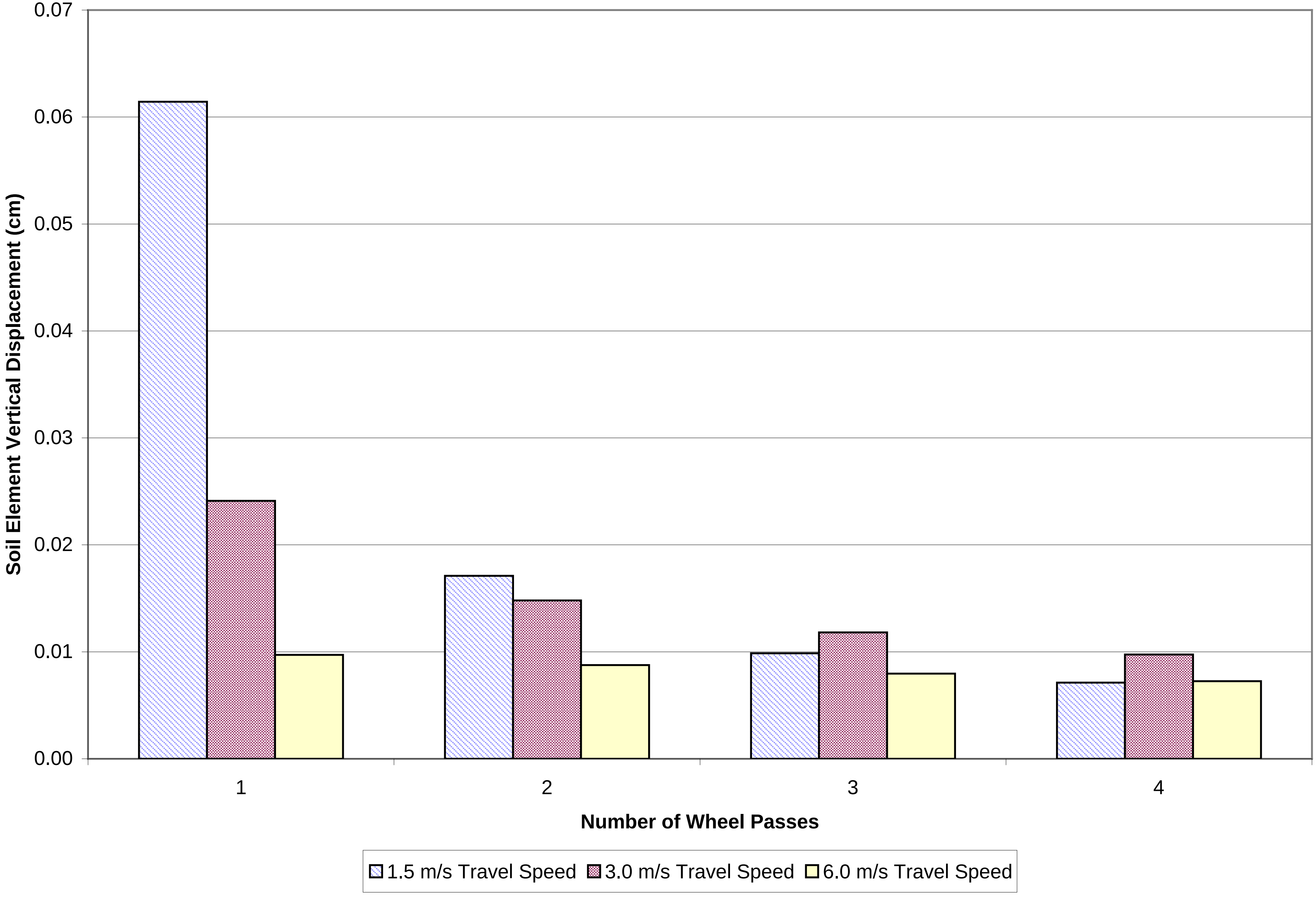
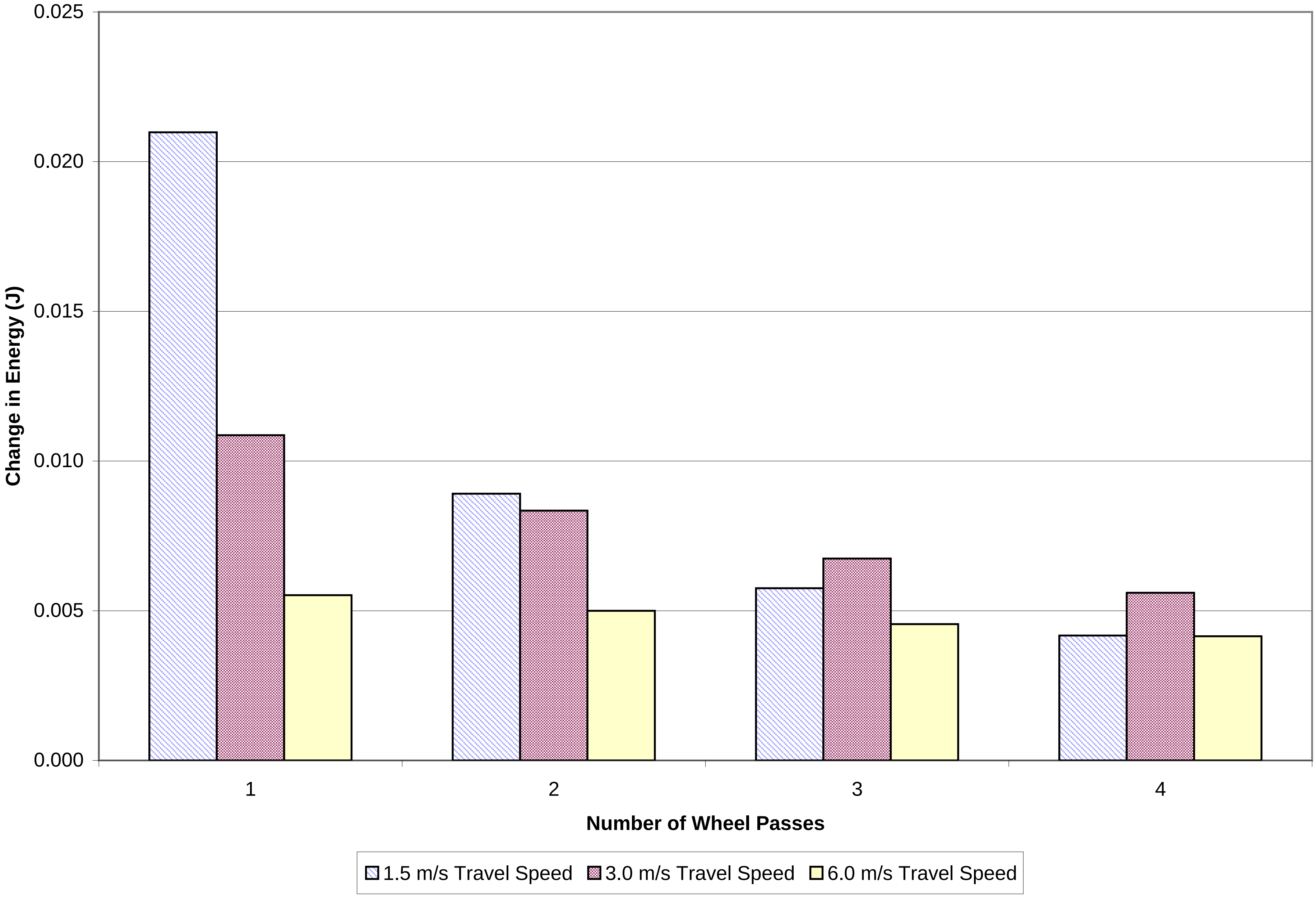
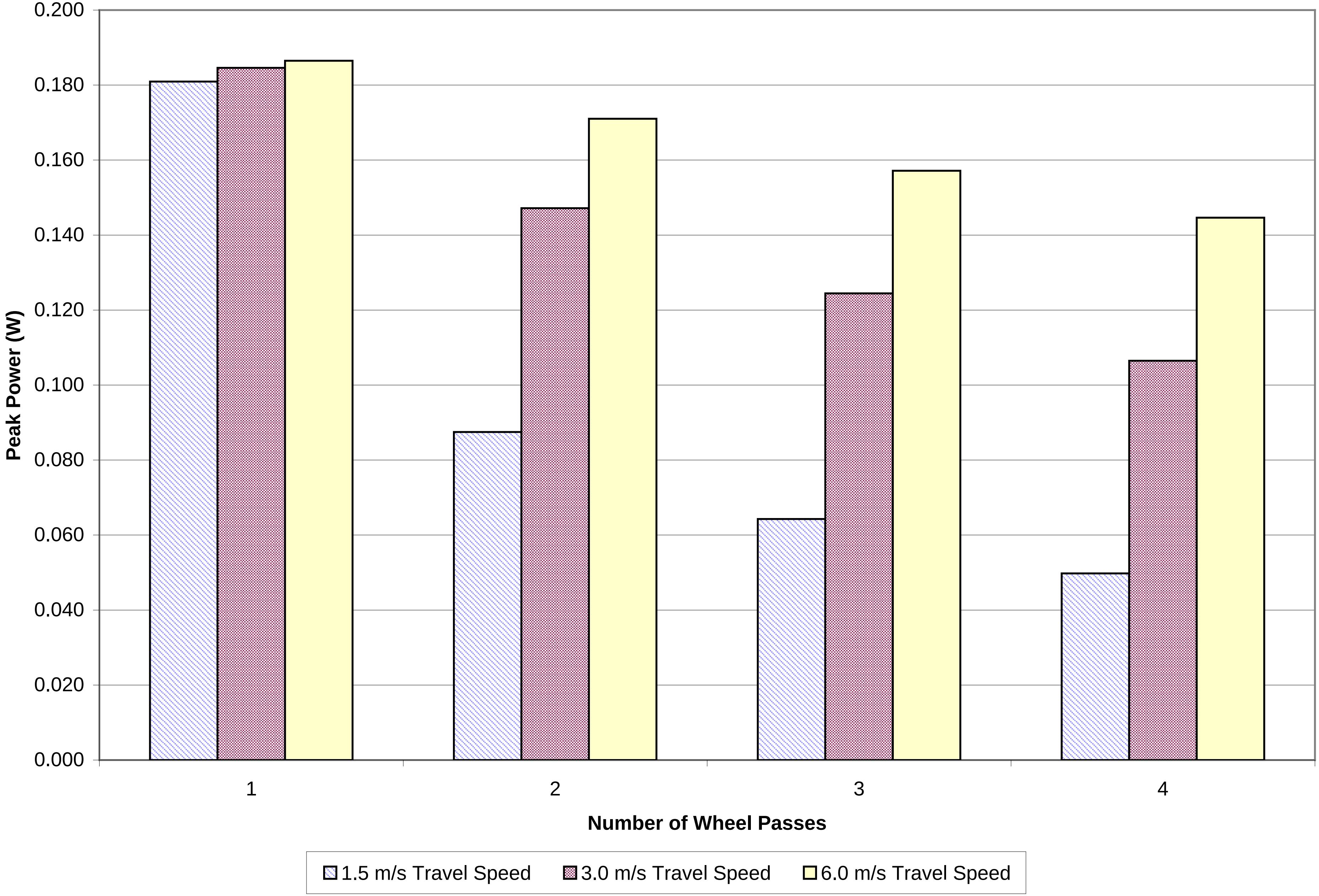
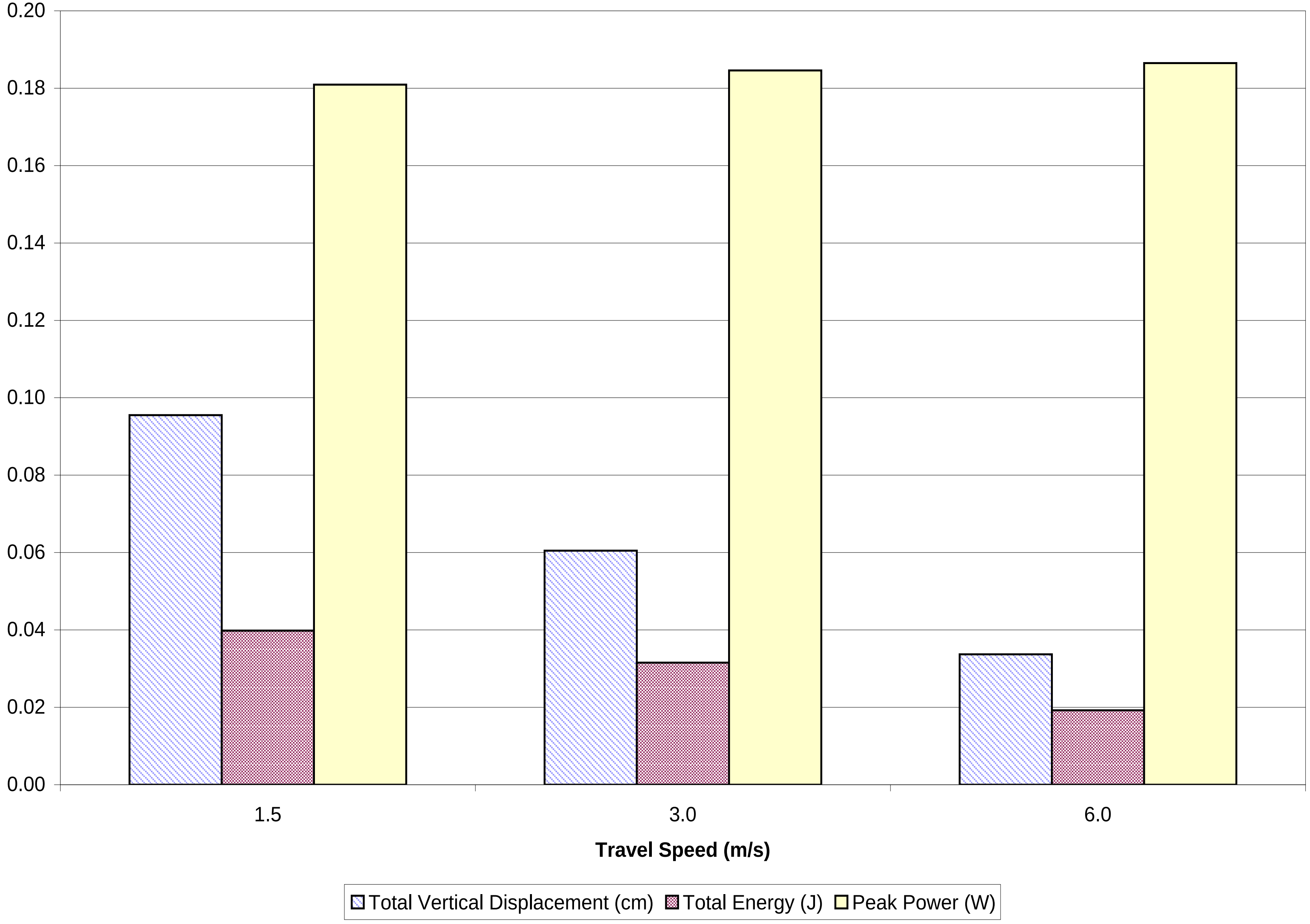

0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Soil Element Vertical Displacement (cm)
1
2
3
4
Number of Wheel Passes
1.5 m/s Travel Speed
3.0 m/s Travel Speed
6.0 m/s Travel Speed


0.025
0.020
0.015
0.010
0.005
0.000
Change in Energy (J)
1
2
3
4
Number of Wheel Passes
1.5 m/s Travel Speed
3.0 m/s Travel Speed
6.0 m/s Travel Speed


0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
Peak Power (W)
1
2
3
4
Number of Wheel Passes
1.5 m/s Travel Speed
3.0 m/s Travel Speed
6.0 m/s Travel Speed



0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1.5
3.0
6.0
Travel Speed (m/s)
Total Vertical Displacement (cm)
Total Energy (J)
Peak Power (W)

Benefits of New Soil Model

- Theoretical (soil deformation, energy, power)
- Not dependent of scale
- Real-time modeling
- Include visco-elastic (time constant/rebound)
- Uses existing terrain database with pedo-transfer functions.

Questions

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